Open-Ended Problems: A Future Chemical Engineering Education Approach. J. Patrick Abulencia and Louis Theodore.

5

Fluid Flow

This chapter is concerned with fluid flow. As with all the chapters in Part II, there are several sections: overview, several specific technical topics, illustrative open-ended problems, and open-ended problems. The purpose of the first section is to introduce the reader to the subject of fluid flow. As one might suppose, a comprehensive treatment is not provided although several technical sections are included. The next section contains three open-ended problems; the authors' solutions (there may be other solutions) are also provided. The third (and final) section contains 42 problems; *no* solutions are provided here.

5.1 Overview

This overview section is concerned—as can be noted from its title—with fluid flow. As one might suppose, it was not possible to address all topics directly or indirectly related to fluid flow. However, additional details may be obtained from either the references provided at the end of this overview section and/or at the end of the chapter.

Note: Those readers already familiar with the details associated with this subject may choose to bypass this Overview.

This section is introduced by examining the units of some of the common quantities that are encountered in fluid flow. The momentum of a system is defined as the product of the mass and velocity of the system.

$$\text{Momentum} = (\text{Mass})(\text{Velocity}) \tag{5.1}$$

The engineering units (one set) for momentum are therefore, lb·ft/s. The units of time rate of change of momentum (hereafter referred to as the rate of momentum) are simply the units of momentum divided by time:

$$\text{Rate of Momentum} = \frac{\text{lb}\cdot\text{ft}}{\text{s}^2} \tag{5.2}$$

The above units can be converted to lb_f if multiplied by an appropriate conversion constant. The conversion constant in this case is

$$g_c = 32.2\frac{(\text{lb}\cdot\text{ft})}{(\text{lb}_f\cdot\text{s}^2)} \tag{5.3}$$

This equation serves to define the conversion constant g_c If the rate of momentum is divided by g_c as 32.2 (lb·ft)/($\text{lb}\cdot_f$ s^2)—the following units result

$$\begin{aligned}\text{Rate of momentum} &= \left(\frac{\text{lb}\cdot\text{ft}}{\text{s}^2}\right)\left(\frac{\text{lb}_f\cdot\text{s}^2}{\text{lb}\cdot\text{ft}}\right) \\ &\equiv \text{lb}_f\end{aligned} \tag{5.4}$$

One may conclude from the above dimensional analysis that a force is equivalent to a rate of momentum [1]. The notation employed in the development that follows are those normally appearing in the chemical engineering literature and will therefore (in many instances) not be redefined.

Fluids are classified based on their rheological (viscous) properties. These are detailed below [1,2]:

1. Newtonian fluids: fluids that obey Newton's law of viscosity, i.e., fluids in which the shear stress is linearly proportional to the velocity gradient [2]. All gases are considered Newtonian fluids and nearly all liquids of a simple chemical formula are considered Newtonian fluids. Newtonian liquid examples are water, benzene, ethyl alcohol, hexane and sugar solutions.
2. Non-Newtonian fluids: fluids that do not obey Newton's law of viscosity; they are generally complex mixtures, e.g., polymer solutions, slurries, etc.

The remainder of this Chapter addresses the following topics:

1. Basic Laws
2. Key Fluid Flow Equations
3. Prime Movers
4. Fluid – Particle Applications

The reader should note that the bulk of the material in this chapter has been drawn from I. Farag, *Fluid Flow*, A Theodore Tutorial, East Williston, NY, originally published by the USEPA/APTI, RTP, NC [2]. In addition, topic (2) – Key Fluid Flow Equations – are highlighted in the presentation to follow.

5.2 Basic Laws

The conservation law for energy finds application in many chemical process units such as heat exchangers, reactors, and distillation columns, where shaft work plus kinetic and potential energy changes are negligible compared with heat flows and either internal energy or enthalpy changes. Energy balances (see two previous chapters) on such units therefore reduce to $Q = \Delta E$ (for a closed non-flow system) or $\dot{Q} = \mathit{\Delta}\dot{H}$ (an open flow system) [3].

Applying the conservation law of energy mandates that all forms of energy entering the system equal that of those leaving. Expressing all terms in consistent units (e.g., energy per unit mass of fluid flowing), results in the total energy balance presented in Equation (5.5).

$$P_1V_1 + \frac{v_1^2}{2g_c} + \frac{g}{g_c} + E_1 + Q + W_s = P_2V_2 + \frac{v_2^2}{2g_c} + \frac{g}{g_c}z_2 + E_2 \qquad (5.5)$$

Equation (5.5) may also be written as

$$\frac{v_1^2}{2g_c}+\frac{g}{g_c}z_1+H_1+Q+W_s=\frac{v_2^2}{2g_c}+\frac{g}{g_c}z_2+H_2 \tag{5.6}$$

or simply

$$\frac{\Delta v^2}{2g_c}+\frac{g}{g_c}\Delta z_1+\Delta H=Q+W_s \tag{5.7}$$

Note that Δ refers to a difference between the value at station 2 (the usually designation for the outlet) minus that at stations 1 (the inlet).

5.3 Key Fluid Flow Equations

5.3.1 Reynolds Number

The Reynolds number, *Re*, is a dimensionless quantity, and is a measure of the relative ratio of inertia to viscous forces in the fluid:

$$\begin{aligned} Re &= \rho VL/\mu \\ &= \mathrm{V}L/v \end{aligned} \tag{5.8}$$

where L = a characteristic length
V = average velocity
ρ = fluid density
μ = dynamic (or absolute) viscosity
v = kinematic viscosity

In flow through round pipes and tubes, *L* is the length and *D* is the diameter. The Reynolds number provides information on flow behavior. It is particularly useful in scaling up bench-scale or pilot plant data to full-scale applications.

Laminar flow is usually encountered at a Reynolds number, *Re*, below approximately 2100 in a circular duct, but it can persist up to higher Reynolds numbers. Under ordinary conditions of flow, the flow (in circular ducts) is turbulent at a Reynolds number above approximately 4000. Between 2100-4000, where the type of flow may be either laminar or turbulent, the predictions are unreliable. The Reynolds numbers at which the fluid flow changes from laminar to transition or to turbulent are termed *critical* numbers. In the case of flow in circular ducts there are two critical Reynolds numbers, namely the aforementioned 2100 and 4000. Different Re criteria exist for geometries other than pipes [2].

5.3.2 Conduits

Fluids are usually transported in tubes or pipes. Generally speaking, pipes are heavy-walled and have a relatively large diameter. Tubes are thin-walled and often come in coils. Pipes are specified in terms of their diameter and wall thickness. The nominal diameters range from 1/8 to 30 inches for steel pipes. Standard dimensions of steel pipe are available in the literature [1,3] and are known as IPS (iron pipe size) or NPS (nominal pipe size). The pipe wall thickness is indicated by the schedule number. Tube sizes are indicated by the outside diameter. The wall thickness is usually given by the outside diameter. The wall thickness is usually given by the Birmingham wire gauge (BWG) number. The smaller the BWG, the heavier the tube.

5.3.3 Mechanical Energy Equation – Modified Form

Abulencia and Theodore [3] provide the following equation:

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \frac{g}{g_c}\Delta z - \eta W_s + \sum F = 0 \tag{5.9}$$

This was defined as the *mechanical energy equation*. Equation (5.9) was rewritten without the pump work and friction terms.

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \frac{g}{g_c}\Delta z = 0 \tag{5.10}$$

This equation was defined as the basic form of the *Bernoulli equation*. Equation (5.9) was also written as

$$\frac{P_1}{\rho}\frac{g_c}{g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho}\frac{g_c}{g} + \frac{v_2^2}{2g} + z_2 + h_s\frac{g_c}{g} + h_f\frac{g_c}{g} \tag{5.11}$$

The h terms were included above to represent the loss of energy due to friction in the system. Frictional loss can take several forms. An important chemical engineering problem is the calculation of these losses. It was noted (earlier) that the fluid can flow in either of two modes – laminar or turbulent. For laminar flow, an equation is available from basic theory to calculate friction loss in a pipe. In practice, however, fluids (particularly gases) are rarely moving in laminar flow.

5.3.4 Laminar Flow Through a Circular Tube

Fluid flow in circular tubes (or pipes) is encountered in many applications, and is always accompanied by friction. Consequently, there is energy loss, indicating a pressure drop in the direction of flow. One can theoretically derive the h_s term for laminar flow [1]. The equation can be shown to take the form

$$h_s = \frac{32\mu vL}{\rho g_c D^2} \tag{5.12}$$

for a fluid flowing only through a straight cylinder of diameter D and length L. A friction factor, f, that is dimensionless, may now be defined (for laminar flow):

$$f = \frac{16}{Re} \tag{5.13}$$

so that Equation (5.12) takes the form

$$h_s = \frac{4fLv^2}{2g_c D} \tag{5.14}$$

Although this equation describes friction loss across a conduit of length, L, it can also be used to predict the pressure drop due to friction per unit length of conduit, i.e., $\Delta P/L$, by simply dividing the above equation by L.

It should also be noted that another friction factor term exists, which differs from that presented in Equation (5.13). In this other case, f_D is defined as

$$f_D = \frac{64}{Re} \tag{5.15}$$

The f_D term is used to distinguish the difference of Equation (5.13) from that of Equation (5.15). In essence:

$$f_D = 4f \tag{5.16}$$

The term f is defined as the Fanning friction factor while f_D is defined as the Darcy or Moody friction factor [4]. Care should be taken as to which of the friction factors are being used in calculations. This will become more apparent shortly. In general, chemical engineers employ the Fanning friction factor; other engineers prefer the Darcy (or Moody) factor. This Chapter employs the Fanning friction factor.

Employing Equation (5.14), Equation (5.11) may be extended in the absence of pump work and rewritten as

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \Delta z \frac{g}{g_c} + \frac{4fLv^2}{2g_c D} = 0 \tag{5.17}$$

The symbols Σh_c and Σh_e, representing the sum of the contraction and expansion losses, respectively, may also be added to the equation as provided below in Equation (5.18). (These effects will be discussed later in this Section).

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \Delta z \frac{g}{g_c} + \frac{4fLv^2}{2g_c D} + \sum h_c + \sum h_e = 0 \tag{5.18}$$

5.3.5 Turbulent Flow Through a Circular Conduit

It is important to note that almost all the key fluid flow equations presented for laminar flow apply as well to turbulent flow, provided the appropriate friction factor is employed. The effect of the Reynolds number of the Fanning friction factor is provided in Figure 5.1. Note that Equation (5.13) appears on the far left-hand side of Figure 5.1.

In the turbulent regime, the “roughness” of the pipe becomes a consideration. In his original work on the friction factor, Moody [4] defined the

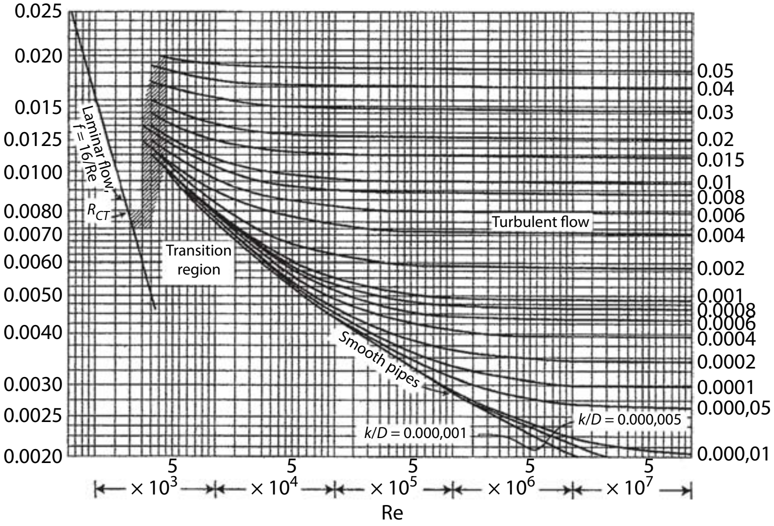

Figure 5.1 Fanning Friction factor (*f*) – Reynolds Number (Re) plot

term *k* (or ε), as the roughness and the ratio, *k/D,* as the relative roughness. Thus, for rough pipes/tubes in turbulent flow:

$$f = f(Re, k / D) \tag{5.19}$$

This equation reads that the friction factor is a function of *both* the Re and *k/D*. However, as can be seen in Figure 5.1, the dependency on the Reynolds number is a weak one in turbulent flow.

5.3.6 Two Phase Flow

The simultaneous flow of two phases in pipes (as well as other conduits) is complicated by the fact that the action of gravity tends to cause settling and "slip" of the heavier phase; the result is that the lighter phase flows at a different velocity in the pipe than does the heavier phase. The results of this phenomena are different depending on the classification of the two phases, the flow regime, and the inclination of the pipe (conduit). As one might suppose, the major industrial application in this area is gas (G) – liquid (L) flow in pipes.

See Abulencia and Theodore [3] for additional details on this class of flow. This topic is revisited in Part III, Chapter 26 – Fluid Flow Term Projects.

5.3.7 Prime Movers

Three devices thay convert electrical energy into the mechanical energy that is applied to various streams are discussed in this section. These devices are: fans, which move low-pressure gases; pumps, which move liquids and liquid-solid mixtures such a slurries, suspensions, and sludges; and compressors, which move (compress) high-pressure gases.

There are three general process classifications of prime movers—centrifugal, rotary, and reciprocating—that can be selected. Except for special applications, centrifugal units are normally employed in industry. These units are usually rated in terms of the four characteristics listed below:

1. Capacity: the quantity of fluid discharge per unit time (the mass flow rate);
2. Increase in pressure, often reported for pumps as *head*: head can be expressed as the energy supplied to the fluid per unit weight and is obtained by dividing the increase in pressure (the pressure change) by the fluid density;
3. Power: the energy consumed by the mover per unit time; and
4. Efficiency: the energy supplied to the fluid divided by the energy supplied to the unit.

Finally, the net effect of almost all prime movers is to increase the pressure of the fluid.

5.3.8 Valves and Fittings

Pipes and tubing (and other conduits) are used for the transportation of gases, liquids, and slurries. These ducts are often connected and may also contain a variety of valves and fittings, including expansion and contraction units. Types of connecting conduits include:

1. threaded;
2. bell-and-spigot;
3. flanged; and
4. welded.

Extensive information on these classes of connections is available in the literature [1,3].

5.4 Fluid-Particle Applications

Fluid-particle studies find wide applications in practice. Consider the following scenario. If a particle is initially at rest in a stationary gas and is then set in motion by the application of a constant external force or forces, the resulting motion occurs in two stages. The first period involves acceleration, during which time the particle velocity increases from zero to some maximum velocity. The second stage occurs when the particle achieves this maximum velocity and remains constant. During the second stage, the particle is not accelerating. This final, constant, and maximum velocity attained is defined as the *terminal settling velocity* of the particle. Most particles reach their terminal settling velocity almost instantaneously. These velocities are given by the following three equations: For the Stokes' law range, i.e., $Re < 2.0$

$$v = \frac{fd_p^2\rho_p}{18\mu} \tag{5.20}$$

For the intermediate range, i.e. $2.0 < Re < 500$,

$$v = \frac{0.153 f^{0.71} d_p^{1.14} \rho_p^{0.71}}{\mu^{0.43} \rho^{0.29}} \tag{5.21}$$

Finally, for Newton's law range, i.e. $Re > 500$,

$$v = 1.74(fd_p\rho_p\rho)^{0.5} \tag{5.22}$$

Note that Re for these equations is based on the particle diameter, d_p. Keep in mind that f denotes the external force per unit mass of particle. One consistent set of units (English) for the above equations is ft/s^2 for f, ft for d_p, lb/ft^3 for ρ, lb/ft·s for μ, and ft/s for v [5].

When particles approach sizes comparable to the mean free path of other fluid molecules, the medium can no longer be regarded as continuous since particles can fall between the molecules at a faster rate than that predicted by aerodynamic theory. Cunningham's correction factor [6] is introduced to Stokes' law to allow for this *slip.*

$$v = \frac{g d_p^2 \rho_p}{18\mu} C \tag{5.23}$$

where C is the Cunningham correction factor (CCF), and

$$C = 1 + \frac{2A\lambda}{d_p} \tag{5.24}$$

The term A is given by $1.257 \times 10^{0.40} \exp(-1.10 d_p/2\lambda)$ and λ is the mean-free path of the fluid molecules (6.53×10^{-6} cm for ambient air). The CCF is usually applied to particles equal to or smaller than 1 micron. Applications include particulate air pollution studies [5] and nanotechnology [7].

5.4.1 Flow Through Porous Media

The flow of a fluid through porous media and/or a packed bed occurs frequently in chemical process applications and represents an extension of the fluid-particle discussion presented previously. Some chemical engineering examples include flow through a fixed-bed catalytic reactor, flow through an adsorption tower, and flow through a filtration unit. An understanding of this type of flow is also important in the study of some particle dynamics applications and fluidization [8,9].

A porous medium is a continuous (relatively speaking) solid phase with many void spaces called pores. Examples include sponges, paper, sand, and concrete. Packed beds of porous material are used in a number of chemical engineering operations, e.g., distillation, adsorption, filtration, and drying. Porous media are divided into:

1. impermeable media: solid media in which the pores are not interconnected, e.g., foamed polystyrene; and
2. permeable media: solid media in which the pores are interconnected, e.g., packed columns and catalytic reactors.

5.4.2 Filtration

Another fluid-particle application involves filtration. This operation is one of the most common chemical engineering applications that involve the flow of fluids through packed beds. As carried out industrially, it is similar to the filtration carried out in the chemical laboratory using a filter paper in a funnel. The object is still the separation of a solid from the fluid in which it is carried and the separation is accomplished by allowing (usually by force) the fluid through a porous filter. The solids are trapped within the pores of the filter and (primarily) build up as a layer on the surface of this filter. The fluid, which may be either gas or liquid, passes through the bed of the solids and through the retaining filter. Abulencia and Theodore [3] provide additional filtration details plus design and predictive equations.

5.4.3 Fluidization

Fluidization is yet another fluid-particle application. It may be viewed as the operation in which a fluid (gas or liquid) transforms fine solids into a fluid-like state. Excellent particle-fluid contact results. Consequently, fluidized beds are used in many applications, e.g., oil cracking, zinc roasting, coal combustion, gas desulfurization, heat exchanges, plastic coating, and fine powder granulation. Once again, Abulencia and Theodore [3] provide details.

A detailed and expanded treatment of fluid flow principles is available in the following two references.

1. P. Abulencia and L. Theodore, *Fluid Flow for the Practicing Chemical Engineer*, John Wiley & Sons, Hoboken, NJ, 2009.[3]
2. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY 2014 [10].

5.5 Illustrative Open-Ended Problems

This and the last Section provide open-ended problems. However, solutions *are* provided for the three problems in this Section in order for the reader to hopefully obtain a better understanding of these problems which differ from the traditional problems/illustrative examples. The first problem is relatively straightforward while the third (and last problem) is somewhat more difficult and/or complex. Note that solutions are not provided for the 42 open-ended problems in the next Section.

Problem 1: A pump is no longer capable of delivering the required flow rate to a system. Rather than purchase a new pump, you have been asked to list and/or describe what steps can be taken to resolve the problem. Replacing the pump is not an option.

Solution: Since replacing the pump is not an option, some of the many other options can include:

1. Carefully check the pump, including the clogging of screens and/or intakes, impellers.
2. Decrease pipe size(s), i.e., the diameter (if feasible).
3. Decrease the pipe length (if possible).
4. Eliminate unimportant valves, expansion and contraction joints, etc.., in order to reduce the pressure drop.
5. Decrease the viscosity of the water by increasing its temperature.

Problem 2: A pressurized airplane flying at an altitude of 35,000 ft experiences a structural failure resulting in the loss of a portion of the external skin of the fuselage. The airplane may be considered a cylindrical vessel, 6 m in diameter and 50 m in length. The area of the hole created in the side of the plane is initially 4 m^2 and is located in the center of the plane, immediately above the wing. The pressure inside the plane before the failure is 1.0 bar and the pressure outside the plane is 0.85 bar. It is estimated that a lateral thrust in excess of 100 Newtons will result in structural failure of the fuselage.

1. Estimate the initial thrust (Newtons) normal to the fuselage when the hole opens up.
2. Determine the maximum area of the hole that can develop prior to structural failure of the fuselage.
3. Specify some design limitations for structural components of the fuselage (ribs and cross braces) based on the results of part (2).
4. Comment on the results.

Solution:

1. The force of the failure is calculated as

$$\text{Force} = (\text{Pressure})(\text{Area}) = (1 - 0.85\ \text{bar})(101.325\text{N/m}^2 \cdot \text{bar})(4\text{m}^2)$$
$$= 60.8\ \text{N}$$

2. The maximum area of a hole that can develop prior to structural failure of the fuselage is based on the maximum thrust that is sustainable without failure:

$$\text{Area}_{\text{max}} = \frac{100\text{N}}{(1\ \text{bar} - 0.85\ \text{bar})(101.325\text{N}/m^2 \cdot \text{bar}}$$
$$= 6.58m^2$$

3. Assuming that rivets connecting skin metal to ribs and cross braces are adequate to withstand forces of a skin failure, one option could include that supports be provided so that unsupported skin sections do not exceed approximately 6 m^2 in area for safety considerations.
4. There are several assumptions in the above solution that need to be carefully reviewed and analyzed.

Problem 3: The suggested method of calculating the pressure drop of gas-liquid mixtures flowing in pipes is essentially that was originally proposed by Lockhart and Martinelli [10]. The basis of their correlation is that the two-phase pressure drop is equal to the single-phase pressure drop for either phase (G or L) multiplied by a factor that is a function of the single-phase pressure drops of the two phases. The equations for the total pressure drop per unit length *Z,* $(\Delta P/Z)_T$, are written as:

$$(\Delta \mathrm{P/Z})_T = Y_G\,(\Delta \mathrm{P/Z})_G \tag{5.25}$$

$$(\Delta \mathrm{P/Z})_T = Y_L\,(\Delta \mathrm{P/Z})_L \tag{5.26}$$

The terms Y_L and Y_G are functions of the variable X:

$$Y_G = F_G(X) \tag{5.27}$$

$$Y_L = F_L(X) \tag{5.28}$$

where

$$X = \left[\frac{(\Delta P/Z)_\mathrm{L}}{(\Delta P/Z)_\mathrm{G}}\right]^{0.5} \tag{5.29}$$

Based on the above equation, the relationship between Y_L and Y_G is therefore given by

$$Y_G = X^2 Y_L \tag{5.30}$$

The single-phase pressure-drops $(\Delta P/Z)_L$ and $(\Delta P/Z)_G$ can be calculated by assuming that each phase is flowing alone in the pipeline, and the phase in question is traveling at its superficial velocity where superficial velocities are based on the full cross-sectional area, *S*, of the pipe. Thus,

$$v_L = q_L/S \tag{5.31}$$

and

$$v_G = q_G/S \tag{5.32}$$

where v_L = liquid-phase superficial velocity
v_G = gas-phase superficial velocity
q_L = liquid-phase volume flow rate
q_G = gas-phase volume flow rate
S = pipe cross-sectional area

Note that either Equation (5.25) or (5.26) can be employed to calculate the pressure drop.

The functional relationships for Y_L and Y_G in Equations (5.27) and (5.28) were also provided by Lockhart and Martinelli [11] in terms of X for phase classification under different flow conditions. For gas-liquid flows, semi-empirical data were provided for the following three flow categories:

1. gas (turbulent flow) – liquid (turbulent flow);
2. gas (turbulent flow) – liquid (viscous flow); and
3. gas (viscous flow) – liquid (viscous flow).

For their correlation [10,11] ϕ_{vv} was expressed as

$$\left(\frac{\Delta P}{Z}\right)_{\mathrm{vv}} = \phi^2_{\mathrm{vv}}\left(\frac{\Delta P}{Z}\right)_{\mathrm{G}} \tag{5.33}$$

where ϕ_{vv} is a function of a dimensionless group, X_{vv}. The magnitude of ϕ_{vv} for values of X_{vv} is provided in Table 5.1.

Convert the above information into equation form.

Solution: The results in Table 5.1 were expressed in terms of Y_L and Y_G, both of which are functions of X_{vv}. VanVliet [14] subsequently regressed the data to a model of the form given below:

$$Y_{G(vv)} = 1.1241 + 3.7085X + 6.7318X^2 - 11.542X^3;\ X < 1 \tag{5.34}$$

$$= 10 - 10.405X + 8.6786X^2 - 0.9167X^3;\ 1 < X < 10 \tag{5.35}$$

$$= -78.333 + 7.3223X + 1.8957X^2 - 0.0087X^3;\ X > 10 \tag{5.36}$$

$$Y_{L(vv)} = 3.9794X^{-1.6583};\ X < 1 \tag{5.37}$$

$$= 6.4699X^{-0.556};\ 1 < X < 10 \tag{5.38}$$

$$= 3.7013X^{-0.2226};\ X > 10 \tag{5.39}$$

The above is just one correlation. The reader is encouraged to attempt to develop an improved set of equations.

5.6 Open-Ended Problems

This last Section of the chapter contains open-ended problems as they relate to fluid flow. No detailed and/or specific solution is provided; that task is left to the reader, noting that each problem has either a unique solution or a number of solutions or (in some cases) no solution at all. These are characteristics of open-ended problems described earlier.

Table 5.1 ϕ_{vv} vs $\sqrt{X_{vv}}$

$\sqrt{X_{vv}}$	ϕ_{vv}
0.2	1.40
0.4	1.69
0.6	1.93
0.8	2.16
1	2.44
2	3.81
3	5.15
4	6.4
6	8.7 (limit of experimental data)
.	.
.	.
.	.
	∞

There are comments associated with some, but not all, of the problems. The comments are included to assist the reader while attempting to solve the problems. However, it is recommended that the solution to each problem should initially be attempted *without* the assistance of the comments.

There are 42 open-ended problems in this Section. As stated above, if difficulty is encountered in solving any particular problem, the reader should next refer to the comment, if any is provided with the problem. The reader should also note that the more difficult problems are generally located at or near the end of the Section.

1. Describe the early history associated with fluid flow.
2. Discuss the recent advances in fluid flow technology.
3. Select a refereed, published article on fluid flow from the literature and provide a review.
4. Provide some normal everyday domestic applications involving the general topics of fluid flow.
5. Develop an original problem that would be suitable as an illustrative example in a book on fluid flow.
6. Prepare a list of the various books which have been written on fluid flow and/or fluid mechanics. Select the three best and justify your answer. Also select the three weakest books and justify your answer.
7. Develop a new experimental method to determine the viscosity of a liquid.
   Comment: Carefully review the experimental methods currently employed.
8. Develop a new experimental method to determine the viscosity of a gas.
   Comment: Carefully review the experimental methods currently employed.
9. Develop an equation to describe the viscosity of a slurry.
   Comment: Give due consideration to the concentration, shape and size distribution of the solids.
10. Describe the role surface tension plays in fluid flow.
11. Define and discuss in technical terms, the differences between Newtonian, pseudoplastic, dilatant, and Bingham plastic fluids.
12. Define and discuss in layman terms, the differences between Newtonian, pseudoplastic, dilatant, and Bingham plastic fluids.

13. Develop a new manometer for pressure (drop) measuring purposes.
    Comment: Carefully review the manometer writeup in Abulencia and Theodore's text [3].
14. Develop a new valve for flowing fluids.
15. Develop a new valve for two-phase flow.
16. Develop a new valve for high-viscosity fluids.
17. List some of the decisions that should come into play in the selection of a flow measure device.
18. Describe the various velocity profiles that can develop with flow through a conduit.
19. Discuss the differences between a fan, a pump, and a compressor.
20. Develop a better method of describing the classification and description of pipe standards.
21. Should the Reynolds number be based on the average or maximum velocity in a pipe/conduit? Justify your answer.
22. Describe at least two methods that can be used to determine the gas flow rate in a large underground pipe.
23. One of the authors [12] has argued that adding fine particulates to a gas flowing in a pipe will reduce its pressure drop. Comment on the proposal.
24. Develop/design a new fitting.
25. Develop/design a new steam trap.
    Comment: Review the steam trap literature.
26. Generate an equation describing the effect of both Reynolds number and pipe roughness on the Fanning friction factor.
    Comment: Refer to the literature [3].
27. Develop a general pressure drop equation for conduit flow where the cross-sectional area of the conduit varies.
28. Consider flow through a number of pipes or conduits of varying cross-sectional areas that are arranged in both series and parallel format. Develop a general equation describing the pressure drop across this system.
29. A fan is no longer capable of delivering the required flow rate to a system. Rather than purchase a new fan, you have been asked to list and/or describe what steps can be taken to resolve the problem. See also Problem 1 in the previous Section.
30. Define compressible flow and discuss the role it plays in fluid flow applications.

31. Discuss the advantages and disadvantages of the various methods employed to describe the size of a particle.
32. Define and discuss the differences between sedimentation, centrifugation, and flotation.
33. With reference to porous media, provide an explanation in layman terms of the difference(s) between porosity, void fraction, solid fraction, and permeability.
34. Derive both the Blake -Kozeny and Burke -Plummer equations. Comment on their validity. Also discuss the differences between the two equations.
35. Develop a new equation to describe the Cunningham Correction Factor as a function of particle size.
    Comment: Refer to L. Theodore's "Air Pollution Control Equipment Calculations" text [5].
36. Generate an equation describing the effect of Reynolds number on the (particle) drag coefficient.
    Comment: Refer to L. Theodore's "Air Pollution Control Equipment Calculations" text [5].
37. Discuss the effect of particle shape on the drag coefficient.
38. Develop a new filtration process for slurries.
    Comment: Carefully review the filtration writeup in Abulencia and Theodore's text [3].
39. Describe the procedure you would follow in an attempt to resurrect a pirate's ship loaded with gold that is located approximately 1.5 miles under the Caribbean Ocean. Comment on the problems that will arise in a project of this nature.
40. One option available to a plant manager when a tube within a heat exchanger fails is to simply plug the inlet of the tube. Develop an equation to describe the impact on the pressure drop across the exchanger as a function of both the number of tubes within the exchanger and the number of plugged tubes.
41. Morgano Consultants designed a crushing and grinding unit to operate with a specific discharge particle size distribution. Once the unit was installed and running, it operated with a different and larger particle size distribution. Rather than purchase a new unit, what options are available to bring the unit into compliance with the specified design size and distribution?
42. Doyle Engineers designed a fan to operate with a discharge pressure of 22 psia. Once the fan was installed and

running, it operated with a discharge pressure of 19 psia. Rather than purchase a new unit, what options are available to bring the unit into compliance with the specified design pressure?

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